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Abstract:

The recent observations of electron anti-neutrinos coming from SN1987A place an extremely stringent limit on the charge of the electron anti-neutrino. At the 90% confidence level, an upper limit of $2.6\mathrm{x}\ 10^{-17} q_e$*, where* q_e *= the electron charge, is derived.*

Supernova 1987A has been a bonanza for astrophysics. The observation of this spectacular event in the Large Magellanic Cloud, being so close to Earth, has provided much information about the processes that trigger supernovae. Of particular importance is the independent and simultaneous observation from two detectors of a prompt pulse of electron anti-neutrinos which arrived at Earth approximately three hours before visible detection of the supernova. In addition to a wealth of information relating to the physics of supernovae, the observation of neutrinos makes it possible to place limits on some of the physical properties of the neutrino itself. Several authors have already studied how this data affects our knowledge of the neutrino mass.[1,2,3,4] The present work investigates the implications of these observations for the neutrino charge.

A total of 19 contained events associated with electron neutrino interactions were observed in the IMB[5] and Kamiokande[6] water Cerenkov detectors over time intervals of six and twelve seconds and energies of 20-40 MeV and 6.3-35.4 MeV respectively. These events were produced via either electron anti-neutrino capture by free protons, $\nu_{e+} + P \Rightarrow$

N + e^+, or elastic scattering, v + e^- => v + e^-. Type-II supernova theory predicts that the fluxes of neutrinos and anti-neutrinos of all flavors are comparable. Since the neutrino capture cross section is about 100 times the elastic scattering cross section, one expects the observed events to be primarily due to electron anti-neutrinos. Further, the observed angular distributions of the events were consistent with isotropy, as expected with capture. Since elastic scattering peeks in the direction of the incident neutrino momentum, we identify events where the electron is came off at an angle inconsistent with the direction of the supernova by more than two standard deviations as due to electron anti-neutrino capture. For this process, the energy of a given positron is very nearly the incident energy of the neutrino plus the mass difference between the proton and neutron; ≈ 1.3 Mev.

Charged electron anti-neutrinos would interact with the galactic magnetic field. The galactic magnetic field is about 1.6×10^{-6} G in magnitude, is roughly constant near our galactic radius, and extends approximately 2 kpc transverse to the galactic plane [7]. The interaction of the charge with this magnetic field would require anti-neutrinos of different momenta to follow different paths from the Supernova to the Earth. Since the observed anti-neutrino pulse lasted only 12.4 seconds, the total path difference between the anti-neutrinos of maximum and minimum momentum must be less than 12.4 light seconds, ≈ 3.4×10^{-11} of the distance the neutrinos traveled in the galactic magnetic field.

There is some uncertainty as to the exact calibration of the Kamiokande clock. The active mass of the IMB and Kamiokande detectors is 5×10^6 kg and 2.17×10^6 kg respectively. If the events in these two detectors did not overlap in time, then none of the anti-neutrinos associated with the 8 IMB events produced an event in Kamiokande detector, and the anti-neutrinos associated with the one Kamiokande event above the IMB detector's threshold did not produce any events in the IMB detector. The probability that both of these events occurred is 0.3%. We therefor assume that the Kamiokande and IMB events overlapped in time.

In fact, the time separation between the arrival of the two electron anti-neutrinos with the maximum and minimum momentum was substantially less than 12.4 seconds. If we adjust the Kamiokande clock so that the one Kamiokande event above the IMB detector's threshold came in the middle of the IMB events, the separation between the two events of interest is less than three seconds. With regards to the time separation between the arrival of the peaks of the low and high momentum anti-neutrino pulses, we adopt the most conservative assumption possible; that the time separation equals the width of the observed pulse, i.e 12.4 seconds. Since the arrival times of anti-neutrinos of similar momenta extended over no more than 12.4 seconds, it is reasonable to assume that the anti-neutrino emission time for detectable neutrinos was no more than 12.4 seconds. The assumption that all the anti-neutrinos were emitted at the same instant gives the largest upper limit on the electron anti-neutrino charge and is therefore the one we use.

We will use event #3 in the IMB detector, and event #3 in the Kamiokande detector to set the limit on the charge of electron anti-neutrinos. These events are reported to have energies of 40 ± 10 MeV, and 7.5 ± 2.0 MeV respectively. Assuming anti-neutrino capture, and taking the mass difference between the proton and neutron, as well as recoil into account one obtains[8] $E_{max} = 42.1 \pm 10.4$ MeV and $E_{min} = 8.9 \pm 2.1$ MeV for the corresponding energies of the anti-neutrinos.

The radius of curvature of a charged particle moving in a magnetic field is directly proportional to the momentum of the particle. This fact, together with the short duration of the neutrino pulse, allows a new limit to be put on the electron anti-neutrino charge. Assuming the electron anti-neutrino is an eigenstate of charge conjugation, this limit also applies to the electron neutrino.

The geometrical details of the problem are illustrated in figure 1. The galactic coordinates of SN1987A are galactic longitude $l = 279.6^{\circ}$, galactic latitude $b = -35.0^{\circ}$. To analyze the problem, we choose a right handed coordinate system with the Earth at the origin and the 0° galactic longitude as the x axis.

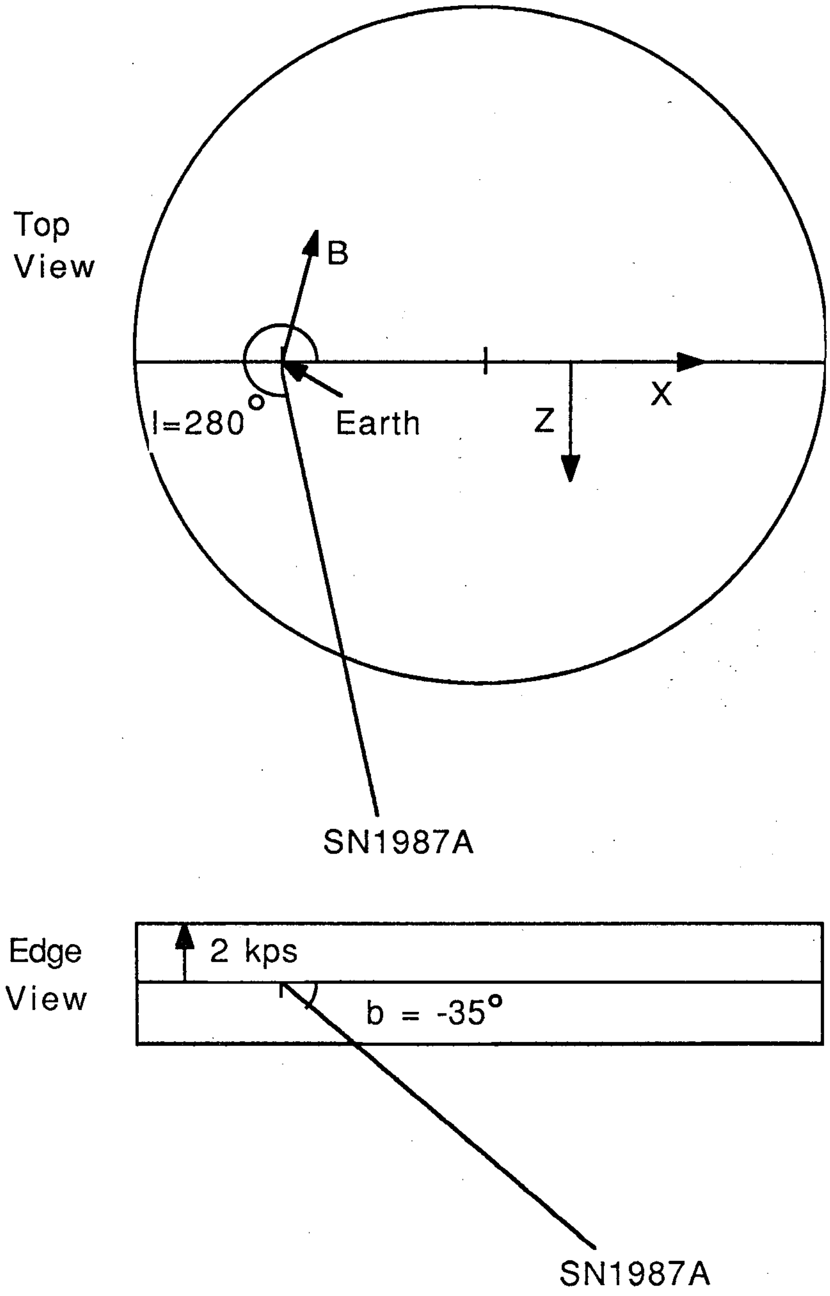

Figure 1

As the figure illustrates, the anti-neutrinos entered the galactic field at an angle of 279.6°, and traveled a distance of 3.49 kpc before reaching the Earth. We assume the galactic field to be uniform over this distance, parallel to the galactic plane, and to have a magnitude of 1.6×10^{-6} G. We also assume that the galactic field is hard edged and that all the anti-neutrinos left the supernova at the same instant. Lastly, we assume that the neutrino's mass is so small that time delays in the flight are entirely due to the effect of the charge interacting with the galactic magnetic field. These assumptions are reasonable and conservative as they are consistent with our knowledge of the galactic magnetic field and require the largest upper limit on the anti-neutrino charge.

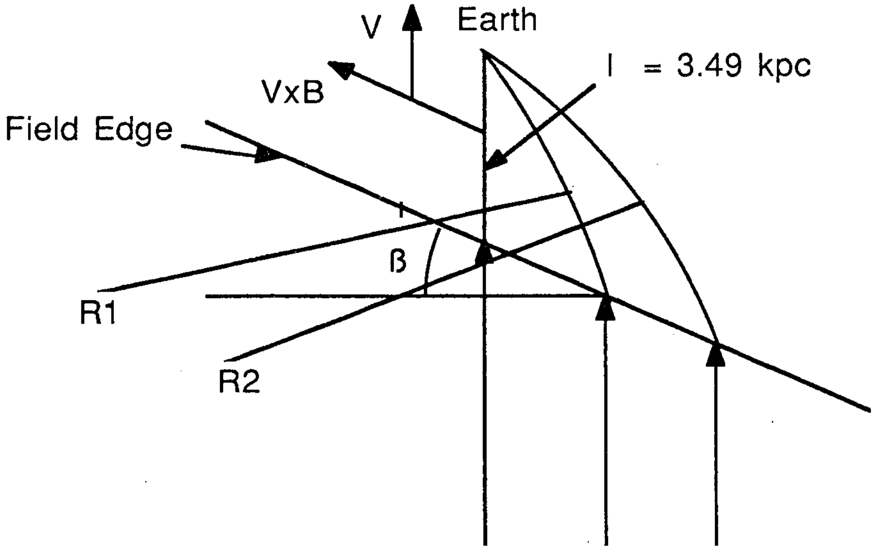

Figure 2

Figure 2 shows the plane in which the anti-neutrinos move. The situation is quite complicated in general. Galactic center is not in this plane and the galactic field is not normal to it. Fortunately, SN1987A happens to be situated so as to simplify the problem. The direction of local component of the galactic magnetic field is known to be between the galactic longitudes of 80 and 110°. Since the galactic longitude of the SN1987A is 280°, the anti-neutrinos' velocities, projected onto the galactic plane, are nearly parallel to the galactic field. Since the effect of the field on the particles is weakest when the field are particle velocities are parallel, we conservatively assume that this is the case. Then $ß = 0$ and we have the following relations: $R_1\sin(\theta_1) = L$, $R_2\sin(\theta_2) = L$, $\theta_1R_1 - \theta_2R_2 = c\Delta T$. Where c is the speed of light and ΔT is the time difference between the centriods of the neutrinos of different energies. Lastly, we define N by $N = R_2/R_1$. Using the small angle approximation,one finds:

$$R_1 = \sqrt{\frac{1}{6}\frac{L^3}{c\Delta T}\left(1 - \frac{1}{N^2}\right)}:$$

Taking $\Delta T = 12.4$ seconds, $N = 4.7$ we find:

$$R_1 = 2.3 \times 10^5 \text{ kpc}.$$

The Lorentz force law requires:

$$q_{ve} = \frac{E_{1,2}/c}{R_{1,2} B \sin(\Delta)},$$

Where $E_{1,2}$, $R_{1,2}$ are the energy and radius of either anti-neutrino 1 or 2, q_{ve} is the anti-neutrino charge, B is the strength of the galactic magnetic field, and Δ is the angle between the field and the particle trajectory, which, taking $ß = 0$, is $\approx 235^o$.

The experimental quantities are the duration of the pulse and the momenta of the anti-neutrinos. As already pointed out, the assumption related to the time separation between the distributions of anti-neutrinos with E_1 and E_2 is so conservative that any remaining uncertainty does not affect the estimation of the upper limit. Further, all astrophysical assumptions are also so conservative that errors in these quantities need not be considered in the determining the confidence levels. Since the errors associated with the E_1 and E_2 are known, assuming Gaussian statistics, the error associated with the ratio of these measurements may be determined. This allows one to determine a confidence level for any value of E_2/E_1. Each value of this ratio corresponds to a possible value of N and hence the anti-neutrino charge limit. The confidence level of this limit is the same as the confidence level of the ratio used to compute it.

Figure two shows the confidence level vs. the upper limit on the anti-neutrino charge. The charge limit corresponding to the 90% confidence level is 2.6×10^{-17} q_e, where q_e is the electron charge.

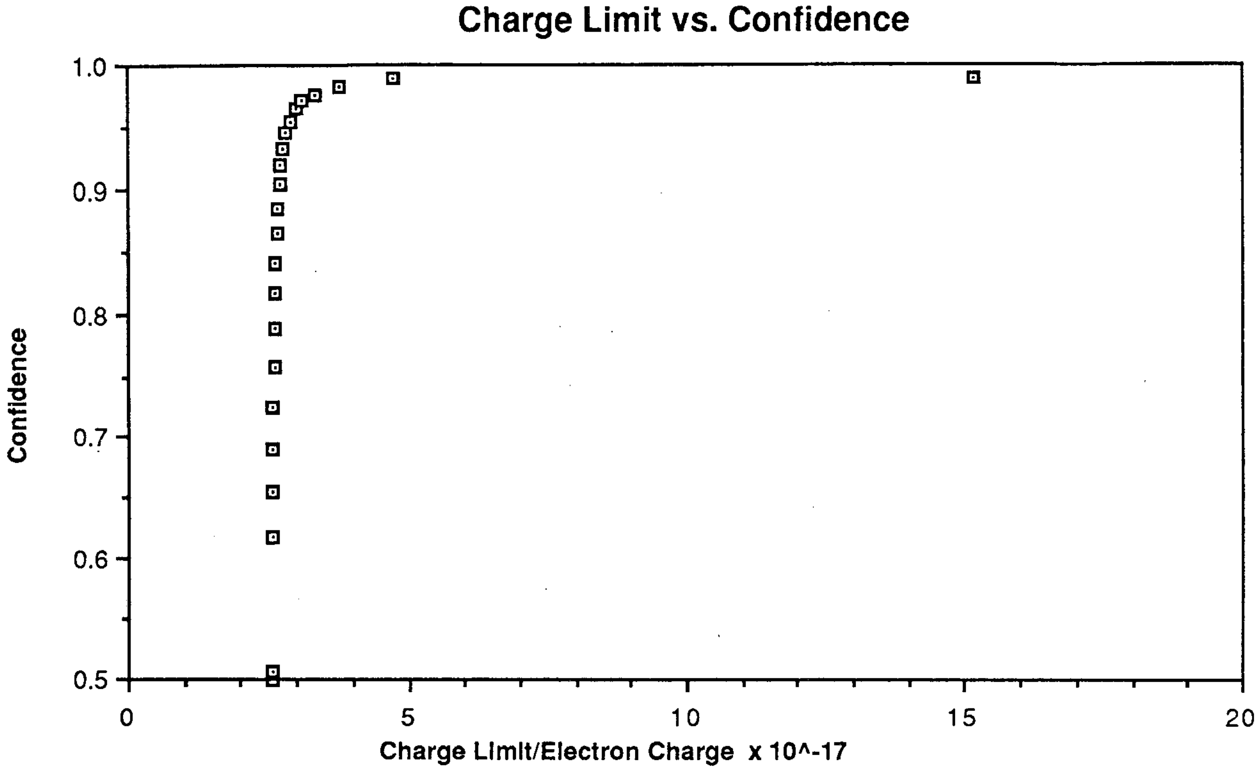

Figure 3

The previous limit on the anti-neutrino charge[9] was 4 x10^{-17} q_e and assumed charge conservation in the reaction n => P + e^- + v_{e+} . The limit reported here, being a direct measure of the anti-neutrino charge, does not require this assumption.

It should be noted that there is likely to be a galactic magnetic field associated with the Large Magellanic Cloud. Further, there may be magnetic fields associated with inter-galactic space. Should the such fields exist in fact, the charge of the electron anti-neutrino would be constrained to be even smaller. Also, it has recently been suggested that the neutrinos from SN1987A arrived in regular pulses with a period of 8.9 ms.[10] This periodicity would presumably arise from the rotation of the core of the exploding star. Should such a periodicity be confirmed by the discovery of a pulsar at the location of the Supernova with the same period, the upper limit of the neutrino charge would be decreased by approximately another order of magnitude.

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